

### Propulsion Materials

## Advanced Magnets

NASA Marshall Space Flight Center



Innovations in magnet design and use of magnetic materials will enable advanced propulsion systems for exploration vehicles and hardware. Propulsion mechanisms that use or generate magnetic fields are critical for many promising space propulsion systems. Strong static magnetic fields can be used to control exhaust velocities in nozzles, and dynamic systems can provide thrust. Advanced propulsion systems require magnets that produce fields with higher specific energies and magnets made of materials that can survive extreme operating environments, including interactions with harsh propellants, radiation exposure, and vacuum exposure. Strong magnetic fields can be produced by low-temperature binary metal alloys or high-temperature ceramic oxide superconducting windings.

### Task Description

As part of tests completed on a high-temperature superconducting (HTS) magnet, these parameters relevant to NASA propulsion were measured:

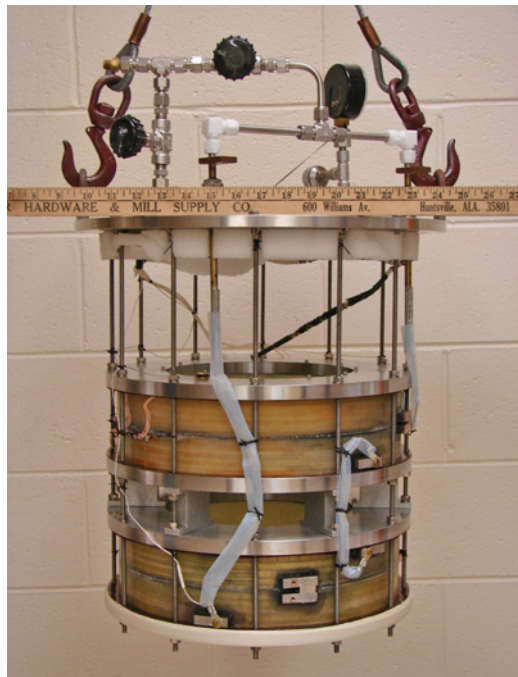
1. Specific energy ( $W_m$ )
2. Critical current
3. Magnetic field profile.

This 7-month study was completed in September 2005.

### Results

As a first step, investigators performed tests on an available magnet developed for a space experiment under a previous NASA Small Business Innovation Research (SBIR) by Intermagnetics General Corporation, in Latham, New York, a leading developer of custom HTS magnet systems. Although this magnet was not developed for use in a propulsion system, it gave materials scientists the opportunity to set up an experiment and measure parameters of interest to propulsion researchers.

The magnet, a powder-in-tube HTS conductor composed of  $(\text{Bi, Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_x$  BSCCO 2223, was cooled to liquid nitrogen temperatures, and current was applied to the magnet windings to create a magnetic field. A magnetic profile was created to show the three-dimensional profile of the magnetic field inside the magnet when 5.1 A and 10.1 A of current were applied to the magnet.



This system consisted of two sets of high-temperature superconducting coils that were donut-shaped and stacked on top of each other with a space between them. In the laboratory, the magnet was cooled to 77 K, and a current was applied.

advanced materials for exploration

# ADVANCED MAGNETS

Parameters	Value/Description	Parameters	Value/Description
Coil Type	Split Pair Helmholtz	Coil Section Width	82.0 mm
Coil Construction	Pancake	Gap Between Coil Sections	70.0 mm
Field Modification	Fe End Plates	Conductor Required	2800 m (nominal)
Winding Inner Diameter	235.0 mm	Operating Temperature	64 K (min)
Winding Outer Diameter	325.0 mm (nominal)	Cooling Option	Pumped LN <sub>2</sub>

Parameters of interest for the High-Temperature Superconducting Magnet that was tested

This revealed how the magnetic field varied over the magnet's structure and how it changed with varying current levels. Researchers determined that the magnetic critical current was 270 V at 12.9 A at 1  $\mu$ V/cm, which is a measure of increased heat and thus increased resistance in the magnet windings; this indicates how much current the system can tolerate before the magnetic field becomes unstable. The measurement is affected by the materials comprising the magnet, as well as how the materials are treated and constructed.

The magnetic energy density at 65 K was 0.47 kJ/kg and 0.13 kJ/kg at 77 K. This magnet was not designed to maximize the specific energy, which can reach 5 kJ/kg in optimized magnet systems and up to 30 kJ/kg for the most advanced laboratory terrestrial magnets. A tremendous gain in technology is needed to meet the specific energy requirements for the most advanced propulsion systems, which require orders of magnitude increase in magnetic energy density.

## Potential Future Activities

Magnet requirements need to be developed for promising propulsion systems, such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and the Plasmoid Thruster. The next step would be to complete a thorough trade study that identifies magnet requirements for these and other potential propulsion systems. Once the requirements are identified, researchers could evaluate and select magnet materials and systems for magnetic specific energy, materials compatibility with propellant, temperature, radiation environment, and overall system weight. Candidate materials

should be procured and tested in their anticipated operating environments. As a final step, the best materials identified by the study would be used to design and build a prototype propulsion system with an advanced magnet that could undergo proof-of-concept testing.

To identify magnet requirements, Marshall Space Flight Center materials experts can work on site with propulsion engineers who are designing spacecraft that require advanced magnets. Center laboratories and the Propulsion Research Laboratory have facilities that are ideal for magnet tests and characterization, as well as for further testing of a prototype propulsion system.

## Capability Readiness Level (CRL)

This Advanced Materials for Exploration (AME) task performed laboratory tests and characterization of a high-temperature superconducting magnet (CRL 3). Designing and building a prototype propulsion system with an advanced magnet developed on the basis of trade study results and materials requirements and testing in a simulated space environment would raise the CRL to 7. Elevation of this magnet technology is essential to the development of propulsion systems that require advanced magnets.

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